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The Preliminary Design of the Optical Thomson Scattering Diagnostic for the National Ignition Facility

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The preliminary design of the optical Thomson scattering diagnostic for the National Ignition Facility

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Abstract. The National Ignition Facility (NIF) is a 192 laser beam facility designed to support the Stockpile Stewardship, High Energy Density and Inertial Confinement Fusion programs. We report on the preliminary design of an Optical Thomson Scattering (OTS) diagnostic that has the potential to transform the community's understanding of NIF hohlraum physics by providing first principle, local, time-resolved measurements of under-dense plasma conditions. The system design allows operation with different probe laser wavelengths by manual selection of the appropriate beamsplitter and gratings before the shot. A deep-UV probe beam (λ_0 between 185-215 nm) will optimally collect Thomson scattered light from plasma densities of 5×10^{20} $\mathrm{electrons/cm^3}$ while a 3ω probe will optimally collect Thomson scattered light from plasma densities of 1×10^{19} $\mathrm{electrons/cm^3}$. We report the phase I design of a two phase design strategy. Phase I includes the OTS recording system to measure background levels at NIF and phase II will include the integration of a probe laser.

1. Introduction

A Diagnostic Instrument Manipulator (DIM) based optical Thomson scatting diagnostic (OTS) is being designed for operation at the National Ignition Facility (NIF) to characterize under-dense plasmas [1,2]. The NIF [3] is a 192 laser beam facility that supports the Stockpile Stewardship, High Energy Density (HED) and Inertial Confinement Fusion (ICF) programs.

The OTS will be inserted into the target chamber by a DIM which requires it to have a compact design, see figure 1. The baseline concept of the system includes a blast window, an unobscured collection telescope, transport and focusing optics, two crossed Czerny-Turner spectrometers and a shared optical streak camera photocathode, located inside of an airbox. The collection telescope is an off-axis Schwarzschild design that relays a 50 µm spot (Thomson volume) to the entrance of the spectrometers. One high resolution (~0.6 meter) spectrometer will measure the ion acoustic wave (IAW) feature (e.g. 206-214 nm for a 5ω probe laser) and one low resolution (~0.15 meter) spectrometer will measure a 50 nm band of the electron plasma wave (EPW) feature. The EPW spectrometer range will be tunable from 150-400 nm. The outputs of the spectrometers are relayed to a gated optical streak camera with selectable sweep windows between 3 and 40 ns. The inherent optical path delay between the two spectrometer systems allow the output signals to be superimposed on the same photocathode separated by approximately 5 ns and having a spatial extent of 20mm. The sweep window is selected so that the required temporal resolution is achieved over the complete Thomson recording window established by the probe laser temporal pulse shape (1-5 ns). We report on the current design status and operational performance at NIF.

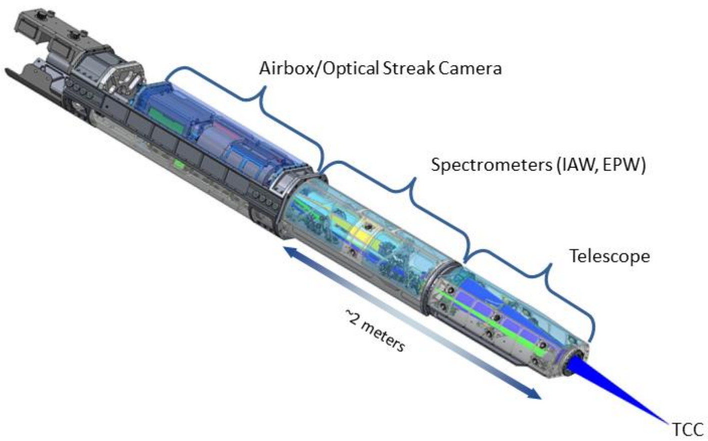

Figure 1. The Diagnostic Instrument Manipulator (DIM) for optical Thomson scattering, which includes the telescope, spectrometer group and the airbox optical streak camera assembly.

2. Optical Design

2.1 Telescope Collection System

The optical design is separated into two major sections, the telescope and the spectrometers. Following the spectrometers is the airbox assembly containing the optical streak camera.

The telescope consists of an off-axis Schwarzschild design of 9.8^{o} allowing an unobstructed view of the targets. The f/8.3 collection optics is the fastest system possible while still maintaining the temporal resolution requirement of 200 ps set by the relationship between the grating illumination of the IAW spectrometer and the telescope focal length. An off-axis parabolic mirror focuses the collimated light onto a pinhole that defines the entrance aperture for the two spectrometers. The system magnification from target chamber center to the streak camera photocathode is 2.0 for the IAW and 2.7 for the EPW. Preceding the telescope is a nominal (100 mm diameter x 8 mm thick) MgF_2 blast window which blocks particulate debris emanating from the laser target interaction during the shot.

2.2 Spectrometer System

The spectrometer group contains two Czerny-Turner type spectrometers that disperse the Thomson scattered light into two distinct bands, the IAW band and the EPW band. The spectrometers share the same 135 μm diameter input aperture pin hole (50 μm in the target image plane) and disperses the bands following a beam splitter that separates the light into two wavelength groups. The deep UV band 150-200 nm is reflected off the front surface and the near UV band 206-214 nm is passed through the splitter. Table 1 is a list of the associated design values for the optical system.

Table 1. Spectrometer design specifications for the optical Thomson scattering system.

Specification	IAW	EPW
Spectrometer size (meter)	0.58	0.14
Spatial extent of recording window (mm)	20	20
Desired bandwidth (nm)	4[a]	50
Wavelength band (nm)	206-214	150-200
Spectrometer resolution ($\delta\lambda/\lambda$)	0.0001	0.01
Nominal grating spacing (gr/mm)	2400	1200
Grating order	2	1
Dispersion at photocathode (nm/mm)	0.2293	4.437
Time resolution (ps)	200	200

[a] The 4 nm band is smaller than the full band. The grating will be adjusted to record any 4 nm band in the overall specified wavelength band.

An unfolded model describes the optical parameters of the optical Thomson scattering collection system is described in figure 2.

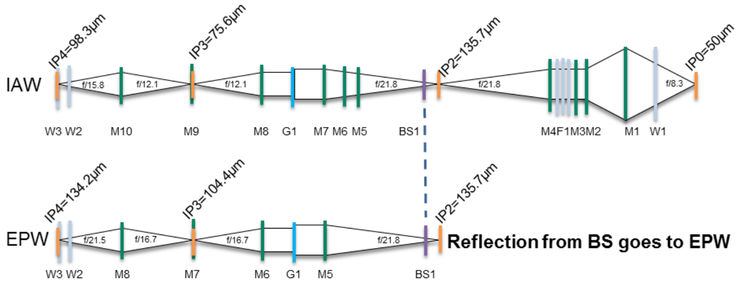

Figure 2. The unfolded optical layout of the NIF DIM based optical Thomson scattering system. The labeled f/#s are based on the beam diameter at the primary (D_1 =154.3 mm). The IAW magnification is optimized for the resolution element of the streak camera recording system measurement to be a nominal ~100 μm.

The (0.14 meter) EPW spectrometer is a low resolution design with expected resolution $\delta\lambda/\lambda$ = 0.00331 and operated in first order. The output of the spectrometer is passed to an intermediate image plane that allows for wavelength masking as required. The image plane is then relayed to the input window of the streak tube for recording.

The (0.58 meter) IAW is the high resolution spectrometer design with expected resolution $\delta\lambda/\lambda$ = 0.00011 and is operated in second order. The image size on the grating also sets the temporal resolution limit of 200 ps [4]. The input light is processed from the upstream beam splitter in transmission, dispersed and then directed to an intermediate image plane where the probe wavelength line can be masked. This intermediate image plane is re-imaged onto the photocathode of the streak tube. There is an inherent delay between the two spectrometers of approximately 5 ns where the EPW is recorded first and the IAW is recording second on the same recording window.

Figure 3 describes the expected resolution of the two spectrometers when a point source is placed at the spectrometer entrance pinhole. The nominal gratings for this evaluation are 2400 gr/mm in second order for the IAW and 1200 gr/mm in first order for the EPW. The two IAW spectral lines for this evaluation are 210 nm and 210.021 nm and the two spectral lines for the EPW are 175 nm and 175.5 nm.

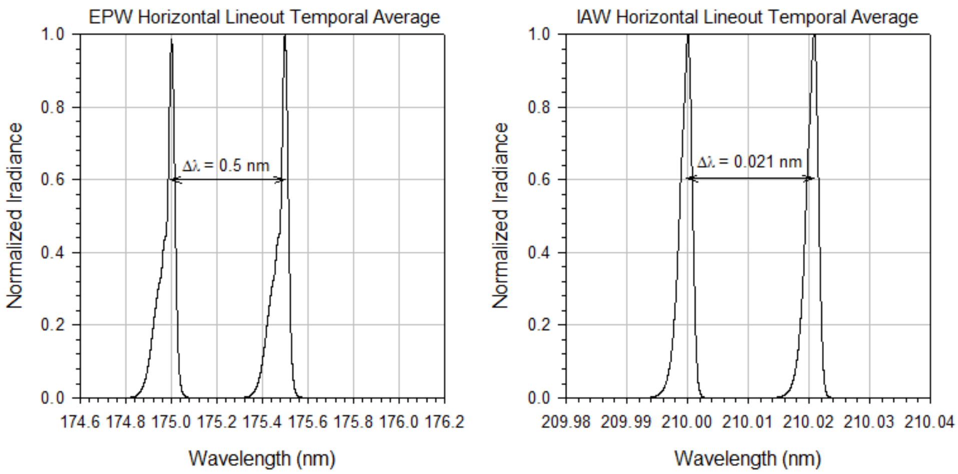

Figure 3. Plots of the dispersion from the two spectrometers onto the photocathode of the streak tube. The left figure is the EPW response and the right figure is the IAW response. Two point source spectral lines for each band were placed at the entrance aperture and the

output averaged along the temporal direction was measured at the photocathode. For the IAW, the lines were 210 nm and 210.021 nm and the EPW lines were 175 nm and 175.5 nm. The IAW gratings for this evaluation were 2400 gr/mm in second order and 1200 gr/mm in first order for the EPW.

The spectrometer optical systems operate in reflectance except for the beam-splitter in the IAW leg, the entrance widow into the airbox and streak tube photocathode window. To fit the spectrometers in a DIM based system, the light paths are out of plane as the beam passes through their respective input and output imaging arms. A "flat" model in figure 4 describes the optical layout.

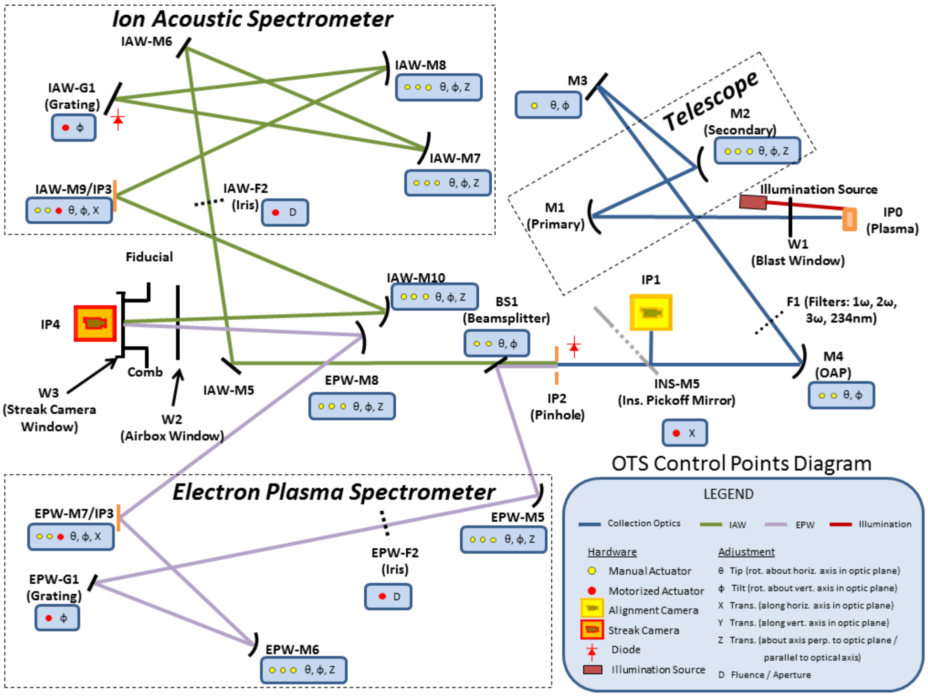

Figure 4. The folded flat model of the NIF DIM based optical Thomson optical detector system. The configuration includes the telescope, two spectrometers and optical streak camera in an airbox.

3. Recording System

The recording system for the Thomson scattering is an optical streak camera utilizing a Photonis, Inc. P510 sealed streak tube with an S20 photocathode deposited on a CaF_2 window. The streak tube is driven by four selectable sweep windows that range from 3 ns to 45 ns. The data from each spectrometer is recorded in the same sweep window with the IAW spectral content arriving approximately 5 ns later than the EPW spectral content. The spectrometers are designed to generate the dispersion band over a 20-mm region in the spatial direction of the streak tube. The nominal resolution element of the recording system is 100 μm defining the total number of recording elements as 200. Along with the recording of spectral content, an optical comb pulse (1 GHz) and a fiducial pulse are injected along opposite edges of the recording window. The streak tube is coupled to a Spectral Instruments SI1000 scientific grade CCD camera and the pixels are binned (3x3) which generates a "super pixel" of 27 μm. The volume between the airbox window and the cathode window is filled with nitrogen to allow the deep-UV wavelengths to propagate from the airbox window to the cathode window with minimal absorption. Figure 5 shows the optical streak camera mounted in a DIM airbox.

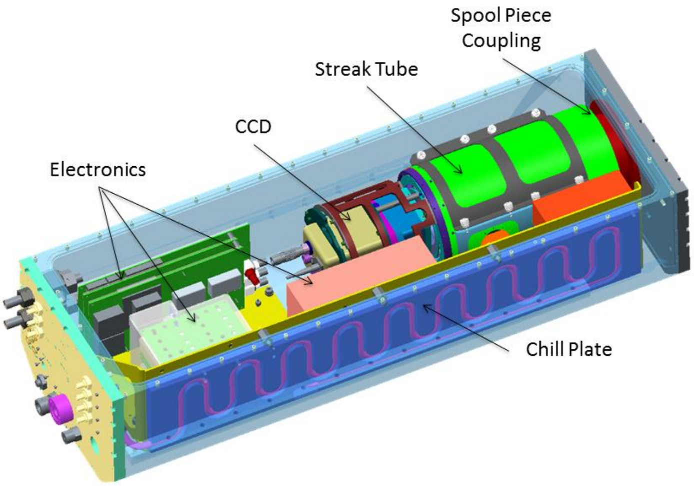

Figure 5. The optical Thomson scattering airbox and streak camera. The airbox input window is a CaF_2 and is coupled to nitrogen gas tube that allows for deep UV light propagation to the input window of the streak tube.

Simulated response from a NIF hohlraum target has been generated using the expected system throughput, quantum efficiency and estimated back ground levels. The synthetic data described in figure 6 shows the temporal separation between the EPW and IAW spectrometers and their nominal wavelength band.

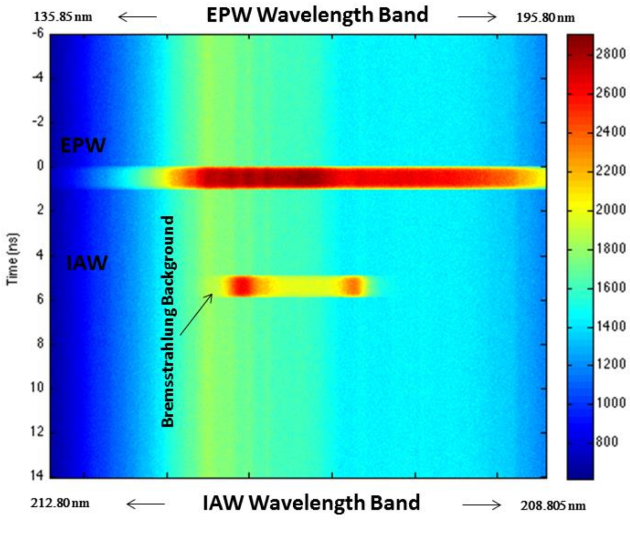

Figure 6. Simulated recorded optical Thomson scattering data as expected on the 30 ns recording window. The data includes quantum efficiency, background levels, the expected noise levels and expected system throughput.

4. Alignment

The DIM based optical Thomson scattering system is aligned to target chamber center through the NIF Advanced Tracking Laser Alignment System (ATLAS). The alignment system has a large field-of-view of the target chamber and can register in three dimensions the DIM locations in either the equatorial or polar positions to an accuracy of better than 200 μm. Figure 7 shows the field-of-view coverage of the OTS system when inserted into the target chamber. A more detailed alignment is completed using an internal alignment camera that views the pinhole image plane.

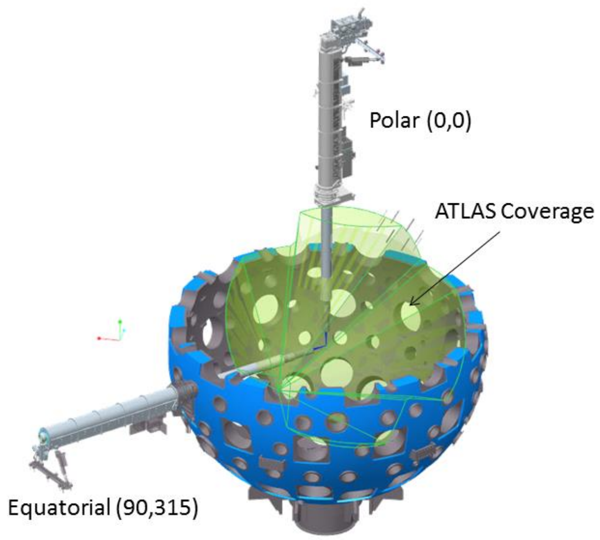

Figure 7. Description of the ATLAS field-of-view for optical Thomson scattering. The alignment system has full coverage for both the equatorial and polar DIM locations. Alignment accuracy is better the 200 μm in X,Y,Z positioning.

5. Summary

An optical Thomson scattering system is being designed to measure the IAW and EPW features of various plasma environments generated at the NIF. The recording system resides inside a NIF DIM and can be operated in the equator or the polar locations. The system will operate in the deep-UV and provide temporal information during the plasma evolution. The system will be implemented in two phases, where phase I will be used to measure the NIF background environment in the deep UV and make Thomson scattering measurements using a 3ω probe. Phase II implementation shall include a UV laser operating at the 5th laser harmonic.

6. References

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